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AIR POLLUTION EFFECTS OF INCINERATOR FIRING PRACTICES AND COMBUSTION AIR DISTRIBUTION

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Cincinnati, Ohio

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by S

Andrew H. Rose, Jr., Robert L. Stenburg,
Morton Corn, Ronald R. Horsley, Daniel R. Allen,
and Paul W. Kolp

A study is under way to determine the relationships between incinerator design criteria and resulting atmospheric contaminant discharges. Tests are made by burning a fuel of constant composition in a prototype multiple chamber incinerator under controlled conditions. Effects of variables are measured by analyzing the flue gases for solids, hydrocarbons, oxides of nitrogen and carbon monoxide.

The series of tests herein reported was made to (1) provide information on the relative importance of such variables as stoking and amount of fuel per charge insofar as they affect the production of atmospheric pollutants, and (2) evaluate the chosen levels of variables such as excess combustion air, underfire and secondary air distribution, and fuel charging rate.

Production of particulates was found to be highly dependent on the amount of excess combustion air and the percentage of this air entering under the fuel bed. At the 50% excess air level particulate discharge increased when underfire air was increased from 15% to 30% of the total combustion air. This did not hold true for the 150% excess air level.

The reduction in the formation of hydrocarbons and carbon monoxide appeared to be more dependent on the level of excess combustion air available than on its distribution between overfire, underfire and secondary air. These pollutants were produced under combustion with 50% excess air but not with 150% excess.

The production of oxides of nitrogen was found to be dependent on the rate of fuel charging, the amount of excess air, and the ignition zone gas temperature.

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AIR POLLUTION EFFECTS OF INCINERATOR FIRING PRACTICES AND COMBUSTION AIR DISTRIBUTION

Andrew H. Rose, Jr.1/, Robert L. Stenburg2/, Morton Corn3/, Ronald R. Horsley3/, Daniel R. Allen3/, Paul W. Kolp3/

Atmospheric pollutants produced from the incineration of municipal and industrial refuse include solid, liquid and gaseous compounds formed by the volatilization, destructive distillation or incomplete combustion of the various components. Through proper incinerator design and operation it should be possible to reduce atmospheric discharge of these contaminants. At present there is a lack of generally accepted incinerator design standards and of criteria for minimizing discharge of atmospheric pollutants. Similarly there are no generally accepted firing practices for incinerators.

To more rapidly develop these standards and criteria, the U. S. Bureau of Mines is studying the single chamber incinerator at the same time that the Public Health Service is studying the multiple chamber type.

This report covers the first phase of the multiple chamber incinerator study, which was to obtain on a test incinerator of fixed dimensions, information on the effect of varying (1) amount and distribution of combustion air, (2) burning rate as measured by the amount of fuel charged per hour, (3) amount of fuel per charge, and (4) the interval between stoking* the burning fuel bed. Phases to be studied later are effects of varying dimensions, velocities and temperature gradient.

* - Stoking refers to stirring of the entire fuel bed.

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EXPERIMENTAL INCINERATOR

A small, refractory lined, multiple chamber prototype incinerator was constructed (Fig. 1) based on the relationships proposed by Rose and Crabaugh[1]. The unit has a grate area of 8.5 sq. ft. with a primary ignition chamber to secondary combustion chamber volume ratio of 1.06. The ignition chamber has a length to width ratio of 2. The elliptical arch was designed to concentrate heat developed in the ignition chamber onto the front third of the grate for more rapid ignition of incoming fuel. The front two-thirds of the grate slopes down 30° from the charging door to a horizontal dumping grate at the rear of the ignition chamber. Fuel is charged through a front-opening guillotine type door. The unit is built in sections formed by pouring 4 inches of high temperature castable refractory onto sheet steel frames. These are bolted together and can be easily disassembled to permit changing physical dimensions with a minimum of new construction.

The present arrangement employs an in-line design with a down-pass mixing chamber located immediately behind the ignition chamber. The mixing chamber is followed by the final combustion or expansion chamber (Fig. 2). Combustion gases from the ignition chamber pass through a high velocity throat over the bridge wall, travel downward through the mixing chamber, and horizontally under a curtain wall to enter the bottom of the final combustion chamber. These gases then travel upward to discharge at the top of this chamber through a short breeching into the stack.

COMBUSTION AIR

Overfire combustion air is introduced to the front of the ignition chamber (under the charging door) at the grate level, and sweeps the surface of the burning fuel bed. Underfire air enters through the ash pit and passes up through the fuel bed. Secondary air is introduced through a duct built into the top of the bridge wall and discharges through a series of ports opening into the top of the mixing chamber. All combustion air entries to the incinerator are fitted with calibrated ducts to permit control and measurement of the air flow supplied at each point (Fig. 3). Thermal anemometers mounted inside each duct meter the flow separately for primary overfire, primary underfire, and secondary air. Strip chart millivolt recorders measure and record the electrical output of the thermal anemometers and indicate the instantaneous flow rate, providing a permanent record of total combustion air flow (Fig. 4).

FUEL

In order to correlate results from this multiple chamber incinerator study with results from the single chamber study of the Bureau of Mines, fuel of essentially the same composition is being used in both studies. It was necessary to select a fuel which would (1) be readily available at both study sites and

(2) be of such a composition that it would produce contaminant responses that would reflect changes in design parameters and operating conditions. The fuel selected consists of newspaper, corrugated cardboard, wood and leafy vegetables (Fig. 5). Equal parts by weight of newspaper and cardboard comprise the paper component which is mixed in a ratio of 3 to 1 with wood chips. Moisture content of each fuel component is determined by a standard toluene extraction method. Using the moisture analyses as a basis, wet leafy vegetables, predominantly lettuce, cabbage and kale, are added in sufficient quantities to raise the entire moisture content of the average fuel mixture to 25%. Newspaper and cardboard are cut in 4-inch squares, and the newspaper is left in compact stacks. The wood component is in the form of hogwood, the majority of this material being chips about 1/4" x 1/2" x 2".

To facilitate charging fuel to the incinerator in accurate quantities, charges were prepared in advance of burning by weighing proportionate amounts of each material in paper sacks (Fig. 6). A sack containing a five-pound charge of fuel with a moisture content ranging from 23% to 27% consisted of 1½ lbs. of newspaper, 1½ lbs. of cardboard, 1 lb. of wood, and 1 lb. of wet vegetables.

All tests in this phase of the study involved 25% moisture content fuel. Future tests will be made employing fuels of up to 50% moisture content.

SAMPLING AND INSTRUMENTATION

Evaluation of effects produced by experimental variables is dependent on collection, sampling and analysis of both solid and gaseous contaminants. Automatic instrumentation was used where feasible to reduce manpower requirements and to obtain continuous records of instantaneous concentrations of certain pollutants (Fig. 7).

Oxygen and carbon dioxide content of the flue gases were continuously measured and recorded using analyzers employing principles based on the paramagnetic properties of oxygen and the thermal conductivity of gases (Fig. 8). Carbon monoxide content was measured by passing a continuous stream of effluent gas through a positive filter type non-dispersive infrared gas analyzer with a range from 0 to 5% and operating at a wave length of 4.4 microns. Hydrocarbon concentrations of the flue gases were monitored by a positive filter type infrared gas analyzer sensitized with hexane and operating at a wave length of 3.4 microns with a range from 0 to 750 ppm (expressed as hexane). Oxides of nitrogen, expressed as NO_2, were determined by the Griess colorimetric method as modified by Saltzman(2). For this determination grab samples of the flue gases were collected in evacuated flasks containing Saltzman reagent.

Particulates in the flue gas were sampled isokinetically at a representative point (Fig. 9). The sampling point was 8 diameters downstream from the breeching and 8 diameters upstream from the top of the stack. Solids were collected on an MSA type 1106-BH glass fiber filter media without organic binder.

Mass determination of the solids was made on an analytical balance, and the volume of gas sampled was measured with a dry type bellows meter. A calibrated orifice meter preceding the gas meter was used to control the instantaneous sampling rate. Corrections were applied for meter temperature, meter pressure, barometric pressure and humidity.

Temperatures of combustion gases were measured (1) at the top of the mixing chamber just after passing the bridge wall throat and ahead of the secondary air inlets, (2) at the bottom inlet to the final combustion chamber after passing under the curtain wall, (3) at the top of the final combustion chamber just before entering the breeching, and (4) in the stack near the particulate and gas sampling points. In order to achieve quick response to temperature changes, the thermocouple mass was kept small by using 30 gauge wires inside a 1/16" o.d. inconel sheath. Hot junctions of the thermocouples were shielded against refractory radiation by triple concentric cylindrical shields made of .012" inconel. Refractory temperatures were measured at three points along the arch length by hot junctions imbedded in the refractory 1/4" from the hot surface and at two points in the final combustion chamber 1" and 1½" from the hot surface.

EXPERIMENT DESIGN

As an initial phase of the long range study, a series of preliminary tests was necessary to provide a sound basis for the selection of certain test procedures and levels of variables which would insure the accumulation of comparative data on the over-all study. Factors of particular concern with regard to firing practices were (1) amount of fuel per charge, (2) combustion rate, and (3) duration and interval of stoke. Factors of concern with regard to combustion air were (1) levels of excess combustion air, and (2) distribution of overfire, underfire and secondary combustion air.

In order to evaluate the effects of these independent variables, a one-quarter fractional factorial experiment with one replication was chosen because it promised the greatest amount of information for the effort expended. Replicate tests were felt to be essential at this stage of the study in order to provide some measure of the degree of reproducibility possible with this type of testing. The variables and the levels chosen for comparison are as follows:

Variables	Levels
Excess air	50% and 150%
Underfire air	15% and 30% of total combustion air
Secondary air	0% and 20% of total combustion air
Fuel per charge	10 lbs. and 15 lbs.
Charging rate	140 lbs/hr.* and 180 lbs/hr.**
Stoking interval	10 min. and 20 min.

* - Equivalent to a grate loading of 16.5 lbs./ft^2 hr.
** - Equivalent to a grate loading of 21.2 lbs./ft^2 hr.

Levels were selected to yield approximately equal effects on contaminant discharges. Thus, it was intended that the effect produced by a change in the level of one variable would not be so large that experimental errors involved in measuring this large effect would obscure the effects produced by changes in levels of the remaining five variables. Limitations in these choices were those inherent in selecting levels of variables about which very little is known. For this reason, two levels of variables, rather than three, were initially selected. On the basis of results yielded by this study, third and fourth levels of variables will be selected to permit more detailed investigation of the contaminant response.

The combinations of testing conditions resulting from this design are shown in Figure 10. Two tests were made with each of the 16 combinations giving a total of 32 tests.

TESTING PROCEDURE

The conduct of all tests followed the same procedure. The incinerator was preheated with soft coal, refuse, or natural gas to raise the refractory surface temperatures to near their operating levels. Weighed amounts of fuel were then charged at predetermined intervals to maintain the desired feed rate. Combustion air was adjusted to the desired amount and distribution, and maintained at this level throughout the test. Although several hours of firing were required to achieve temperature equilibrium of the refractory an inch or more from the hot surface, refractory temperatures only 1/4" from the hot surface stabilized after 30 to 60 minutes of operation on a regular charging schedule. Uniform heat input to the refractory was assumed once this latter condition was realized. With surface refractory temperatures in the arch stabilized and gas temperatures varying uniformly over a given charging cycle, a material balance through the incinerator was made based on (1) the mass gas flow from the stack, and (2) the mass gas input to the incinerator calculated from total combustion air and burning rate. Upon determining that the mass balance was satisfactory, all continuous gas analyzers and the particulate sampling system were started. Nitrogen oxide samples were collected over a convenient charging cycle while gas and particulate sampling was in progress. An average of nine grab samples were taken over one cycle which included the period between two charges of fuel.

FUEL CHARGING TECHNIQUE

In this series of tests, effects of both 10 lb. and 15 lb. fuel charges were studied. The charging procedure involved placement of 5 lb. sacks of fuel, one at a time, in the air lock compartment (Fig. 11). Each sack was then pushed through the charging port into the incinerator and spread out over the front third of the grate. Just prior to introduction of a new charge, material from the previous charge was pushed to the rear section of the grate. At regularly scheduled

intervals the fuel bed was stoked and the fuel spread over the entire grate area. Immediately after stoking, the movable grates at the back were shaken, but only enough to loosen any compacted material.

RESULTS

Results obtained from this series of tests can be interpreted only in terms of the conditions under which the study was made. Tests were limited to a uniformly prepared rubbish of 25% moisture content which was burned under closely controlled conditions of charging and air distribution in a fixed dimension multiple chamber incinerator. It is not known at this time whether or not results reported here will be applicable to municipal and industrial incinerators in general. Correlation between atmospheric discharges produced under these test conditions and the pollutants resulting from full scale incinerators will be made as the study progresses, and as similar emission data are obtained from municipal incinerators operating under actual conditions.

Reproducibility of contaminant occurrence was highly dependent on close control of combustion air to the incinerator. Table 1 compares the nominal and actually achieved air distribution. At the 150% excess air level, where control of air flow was more difficult than at the 50% excess air level, the variation in contaminant samples is correspondingly greater.

All particulate and nitrogen oxide measurements were converted to logarithms to normalize the distribution of experimental errors. The fact that the logarithms of the observations are more nearly normally distributed than the observations implies that experimental errors in measurement are proportional to the contaminant concentration measured.

A tabulation of all major findings is contained in Tables 2A and 2B. The relationship of each contaminant studied to experimental variables is discussed in turn.

1. Solid Contaminants

All conditions of combustion tested gave exceptionally low particulate emissions. In this series, the highest average particulate loading for duplicate tests was 6.1 lbs. per ton of fuel charged, and this occurred at the 50% excess combustion air level with 30% underfire air, 0% secondary air, and a fuel charging rate of 140 lbs./hr.

Evaluation of the significance of the six variables incorporated in the experiment design indicated significant effects on particulate occurrence due to (1) percent excess combustion air, and (2) percent underfire air. By reference to Table 3 it will be noted that there was little or no effect on particulates with an increase of underfire air at the 150% excess air level; but at the 50%

excess air level an increase in underfire air from 15% to 30% (of the total combustion air) caused a 210% increase in particulate loadings (both in lbs. particulate/hr. and in lbs. particulate/lb. of fuel charged). From this it is apparent that underfire air affects particulate loadings at only one of the two excess combustion air levels selected.

There were no significant effects on particulates attributable to (1) fuel charging rate, (2) stoking interval, (3) percent secondary air, and (4) lbs. of fuel per charge.

The standard deviation of experimental errors in particulate determination as computed from duplicate runs was 37.4% for measurements of either lbs. particulate/hour or lbs. particulate/lb. of fuel burned.

The fact that combustion of fuel with 150% excess combustion air at 30% underfire produced appreciably lower particulate loadings than combustion of fuel with 50% excess combustion air at 30% underfire, suggests the need for investigating the effects of high underfire air levels involving excess combustion air at levels of 150% and above.

One of the common concepts regarding particulate discharge from municipal and industrial incineration processes is that total solid emissions result solely from physical entrainment of particles in the gas stream with particulate discharge increasing as gas velocity through the fuel bed increases. In an effort to confirm this concept, the effects on solid discharges of gas velocity through the fuel bed (a function of percent underfire air) were compared at the 50% and 150% excess air levels. At the 50% excess air level the solid discharge was .000739 lbs./lb. fuel at 15% underfire air and .002291 lbs./lb. fuel at 30% underfire air. This increase in particulates with increased underfire air is not present at the 150% excess air level where discharges were .000832 lbs./lb. fuel at 15% underfire air and .000875 lbs./lb. fuel at 30% underfire air. It can be concluded from the discrepancies indicated in this analysis that the concept of physical entrainment of solids as the sole mechanism for producing total solid emissions is not valid. While physical entrainment probably is a mechanism which contributes to the solid discharges, other factors such as volatilization and condensation of inorganic compounds and incomplete combustion also affect the degree of this discharge.

Design of the test incinerator was based on relationships of grate loading, arch height and length to width ratio of ignition chamber, proposed by Rose and Crabaugh[1] as being the most suitable criteria for effecting combustion with a minimum discharge of particulates from incineration processes. The exceptionally low particulate loadings resulting from these tests would tend to substantiate these design relationships for the criteria employed. Dimensions of the test incinerator are shown in Table 5.

2. Hydrocarbons

Hydrocarbons were measured and reported in terms of hexane, the sensitizing gas in the infrared analyzer. It is recognized that a hexane sensitized instrument has zero sensitivity to acetylene and very low sensitivity to ethylene, acetone,

benzene and other organic compounds which are normally encountered in incinerator flue gases. However, this instrument is intended to serve only as an indicator of the changes in levels of organics in general, and is not intended to give a measure of total organics. The measuring system, consisting of the analyzer and millivolt recorder, has a calculated accuracy of ± 17 ppm over the 30 to 750 ppm range. Experience in calibration and sampling indicated that the system could not reliably detect hydrocarbon concentrations of less than 30 ppm.

a. Results at 50% Excess Combustion Air Level

Combustion of fuel at this excess air level produced measurable concentrations of hydrocarbons under all conditions of operation. However, hydrocarbon production was intermittent, each occurrence lasting only one or two minutes depending on the combination of conditions responsible for its production. When air control was good from one charging cycle to the next, the reproducibility of hydrocarbon surges showed a uniform pattern over consecutive cycles (Fig. 12). Maximum concentrations ranging up to 400 ppm were produced with 50% excess air distributed between overfire and underfire. Under the conditions tested, the introduction of 20% secondary air at this excess air level did not produce any discernible change in hydrocarbon emissions.

Brief surges of hydrocarbons in the flue gases occurred when flash burning resulted from both (1) introduction of fuel to the incinerator and (2) agitation of the burning fuel bed. Although the hydrocarbon surge most likely resulted from lowering of oxygen content in the fuel bed combustion zone to levels which precluded complete combustion, the oxygen concentration measured in the stack could not provide sufficiently precise data to establish what these combustion zone oxygen levels were.

In these tests oxygen content of combustion gases averaged 10%. The lowest levels recorded were between 2% and 3% oxygen in the flue gas, but hydrocarbon peaks often occurred at considerably higher recorded oxygen concentrations. In view of the limited sensitivity of the thermal conductivity method of measuring oxygen, it is conceivable that the oxygen content may have been well below these values during brief periods of intense burning. Minimum oxygen levels occurred after charging 15 lbs. of fuel per charge at the 140 lb/hr burning rate.

b. Results at 150% Excess Combustion Air Level

All conditions of combustion at 150% excess air, both with and without secondary air, failed to produce hydrocarbons in excess of the 30 ppm lower limit of detectability of the measuring system (Figure 13). At this level of excess air there was no significant difference in the total amount of hydrocarbons produced by varying (1) the fuel charging rate, (2) the stoking interval, (3) the distribution of combustion air, or (4) the lbs. of fuel per charge.

Oxygen concentration averaged 14% for all tests conducted at the 150% excess air level. The lowest values recorded at this level varied between 6% and 7% oxygen in the stack gas. These values occurred after charging 15 lbs. of fuel/charge during the 140 lb/hr. burning rate.

3. Carbon Monoxide

Accuracy of the carbon monoxide monitoring system including the infrared analyzer and millivolt recorder was calculated to be ± 0.07% CO over the 0.1% to 5% range. Calibration and extended use of the instrument showed that carbon monoxide concentrations lower than 0.1% could not reliably be detected.

Carbon monoxide content of the flue gases followed exactly the same trends as the hydrocarbons. Except for the unexplainable occurrence of carbon monoxide on a single duplicate test, all conditions of combustion at the 150% excess air level failed to produce concentrations of carbon monoxide in excess of the 0.1% lower limit of detectability of the measuring system (Fig. 13).

As was the case with hydrocarbons, combustion of fuel at the 50% excess air level produced intermittent surges of CO for short periods of up to two minutes duration (Fig. 12). The occurrence of measurable amounts of CO in the flue gas was directly traceable to those factors which momentarily reduce the fuel bed combustion zone oxygen content below the level required for complete combustion. In some tests instantaneous CO concentrations reached 3½%, but these peaks were of such short duration that the highest average CO concentration for any single test amounted to only .2%.

As nearly as could be determined by the measuring and recording instruments used, the occurrences of carbon monoxide and hydrocarbon always coincided and were of approximately the same duration.

Application of the findings relating to hydrocarbon and carbon monoxide concentrations can be made to industrial and municipal incinerator design and operating practices. Since combustion at the 50% excess air level produced these contaminants while operation at the 150% excess level produced essentially no detectable concentrations of hydrocarbons or carbon monoxide, it is apparent that these contaminant discharges are a function of proper employment of the combustion air as it relates to (1) distribution within the ignition chamber, and (2) levels of oxygen available in the combustion zone.

4. Oxides of Nitrogen

Up to nine individual stack gas grab samples per charging cycle were collected and used to determine oxides of nitrogen in the stack effluent by a technique employing the reagents recommended by Saltzman.[2] Time between samples was adjusted to assure the measurement of peaks produced by various operating conditions. Grab samples yielded instantaneous values of nitrogen oxides in the

flue gas. An average value of nitrogen oxides concentration representative of incinerator operating conditions during the sampling cycle was obtained by integrating beneath the nitrogen oxides-time of sampling curve.

Preliminary studies indicated that the larger portion of oxides of nitrogen in the stack effluent was in the form of nitric oxide. The reagent recommended by Saltzman is sensitive only to nitrogen dioxide. Laboratory evaluation of the reagent using prepared samples of nitric oxide and nitrogen dioxide in air was undertaken to determine:

(1) NO to NO_2 conversion time

(2) Time required for complete absorption of NO_2 by the reagent.

Stack gas samples were also analyzed to determine if these laboratory findings could be applied to the measurement of oxides of nitrogen in a complex stack gas mixture. The curves in Fig. 14 show the nitrogen dioxide concentrations of three replicate sets of flue gas samples, measured using the Saltzman reagent, after various sample holding times up to forty-eight hours. On the basis of these results and the findings made using prepared gas samples in the laboratory, all subsequent oxides of nitrogen determinations were based on spectrophotometric evaluation of Saltzman reagent absorbance after twenty-four hours had been allotted for complete conversion of NO to NO_2, absorption of the NO_2, and full color development of the absorbing reagent. All oxides of nitrogen are therefore reported as NO_2. A detailed discussion of this work will be published separately.

Variables found to be significant in the formation of nitrogen oxides were excess air and feed rate. There were no distinguishable effects on NO_2 produced by (1) lbs. of fuel per charge, (2) stoking interval, (3) percent secondary air, and (4) percent underfire air. The main effect attributable to excess combustion air was a 12% increase in lbs. NO_2/hr. (.156 lbs./hr. to .17 lbs./hr.) and a 12% increase in lbs. NO_2/lb. fuel burned (.000982 lbs. NO_2/lb. fuel to .001096 lbs. NO_2/lb. fuel).

The main effect attributable to feed rate was a 44% increase in lbs. NO_2/hr. (.137 lbs. NO_2/hr. to .198 lbs. NO_2/hr.) and a 12% increase in lbs. NO_2/lb. fuel burned (.000980 lbs. NO_2/lb. fuel burned to .001098 lbs. NO_2/lb. fuel burned).

The standard deviation of experimental errors computed from differences between nitrogen oxides discharges from duplicate runs was found to be 12.4% for measurements of lbs. NO_2/hour and lbs. NO_2/lb. fuel burned.

Temperature fluctuations of the combustion gases at the bridge wall followed a cyclic pattern which involved a rapid increase of temperature shortly after fuel was charged, and a gradual decrease of temperature as combustion continued. Under all conditions tested, high instantaneous concentrations of nitrogen oxides

in the flue gas occurred when gas temperatures at the bridge wall were high. As gas temperature at the bridge wall decreased, nitrogen oxides concentrations generally decreased. This behavior pattern is illustrated by Fig. 15. In some instances, nitrogen oxides concentration peaked while gas temperature showed no extreme change. This can be explained by the fact that gas temperature at the bridge wall is measured at thirty-two second intervals and sudden temperature fluctuations between measurements escape detection. Also, small localized regions of rapid burning in the fuel bed apparently have a greater relative effect on nitrogen oxides concentration in the stack than on gas temperature at the bridge wall.

In addition to fuel charging, agitation of the burning fuel bed was also responsible for increased burning as revealed by high gas temperatures at the bridge wall and correspondingly high nitrogen oxides concentrations.

The critical temperature associated with nitrogen oxides formation is thought to be in or directly over the fuel bed, but gas temperature at the bridge wall may be a usable indicator of nitrogen oxides concentration in the effluent. Before establishing the relationship between gas temperature at the bridge wall and nitrogen oxides concentration in the effluent, the reproducibility of burning conditions as reflected by these parameters must be firmly established.

Comparison of nitrogen oxides-gas temperature patterns for two complete nonconsecutive charging cycles within the same test shows consistency (Fig. 16). Similarly, comparison of nitrogen oxides-gas temperature patterns for two complete cycles of duplicate tests employing identical operating conditions shows this same consistency (Fig. 17). Consistency is exhibited for similar patterns of all tests, but the degree of reproducibility varies. When duplication of combustion conditions for duplicate runs is good, the resulting patterns are also good. Thus, at the 150% excess air level, where combustion air flow is more difficult to control than at the 50% excess air level, nitrogen oxides-gas temperature patterns indicate greater variation (Fig. 18).

Despite changes in levels of all variables considered in this study, nitrogen oxides concentration in the effluent is highly associated with gas temperature at the bridge wall. For this reason it is felt that gas temperature at the bridge wall is a usable indicator of the order of magnitude of nitrogen oxides concentration in the effluent. It is possible that experimental variables found in this study to be significantly related to oxides of nitrogen emission are effective only through their influence on temperature. Deviations from the desired excess air level cause more or less dilution of the nitrogen oxides, and all concentrations used to evaluate the relationship between nitrogen oxides and gas temperature were corrected to provide a comparative basis for evaluation. The correction applied was:

$$NO_2, \text{ ppm at nominal air level} = NO_2 \text{ (ppm)} \times \frac{\text{(Combustion air, actual)}}{\text{(Combustion air, nominal)}}$$

Figs. 19 and 20 show curves obtained from linear regression analyses performed on values of nitrogen oxides concentration and the corresponding gas temperature at the bridge wall for all samples collected at the 50% and 150% excess combustion air levels, respectively. The method of least squares was used. The resulting straight lines have the following equations:

50% Excess Combustion Air:

$$\text{Log } NO_2 \text{ (ppm)} = 0.0003689T.(°F.) + 1.1625 \pm 0.1253$$

150% Excess Combustion Air:

$$\text{Log } NO_2 \text{ (ppm)} = 0.0004056T.(°F.) + 1.0784 \pm 0.1970$$

There is no major difference between the slopes or intercepts of these curves; however, dispersion of sample points at the 150% excess combustion air level is greater than at the 50% excess air level.

The most significant findings of this study which can be applied to municipal and industrial incineration are the factors affecting the formation of oxides of nitrogen. Three factors found to control this formation were (1) temperature, (2) excess air, and (3) feed rate (grate loading).

The increase in oxides of nitrogen concentration was not linear with temperature but increased as a logarithmic function of temperature. While bridge wall gas temperature was used in establishing this relationship, it is realized that ignition zone temperatures are controlling. Of import to incinerator design, however, is the fact that increased operating temperatures result in increased oxides of nitrogen formation, other conditions being equal.

Increasing the excess combustion air resulted in increased nitrogen oxides formation for a given grate loading, despite the accompanying reduction in temperature. The effect of decrease in temperature with its corresponding decrease in oxides of nitrogen is apparently a less significant shift than the increase in oxides of nitrogen due to higher excess combustion air. This relationship should hold for larger incinerators wherein the temperature decrease will be less for a corresponding increase in excess air since the surface to volume ratio, for heat loss, will also be smaller. From an operational standpoint this effect is significant in that practices of reducing furnace temperatures through the use of high levels of excess air may result in increased total discharge of oxides of nitrogen.

As in the case of excess air, an increase in feed rate resulted in an increase in oxides of nitrogen formation. The cause of this effect, however, is obscured since the ignition chamber temperature also increased with increased feed rate at a given excess air level and the effect may be a result of temperature increase. This effect from the operational and design standpoint, however, is significant in that increased grate loadings can be expected to result in increased oxides of nitrogen emissions.

5. Smoke and Odors

While it is realized that smoke and odor levels from incineration processes do not constitute accurate measurements of contaminant discharges, sufficient observations of both smoke and odors were made during these tests to establish gross levels. Random observations during testing indicated smoke density of the discharge to be essentially zero, and the odor level from the stack discharge was sufficiently low to be undetectable in the immediate vicinity of the stack.

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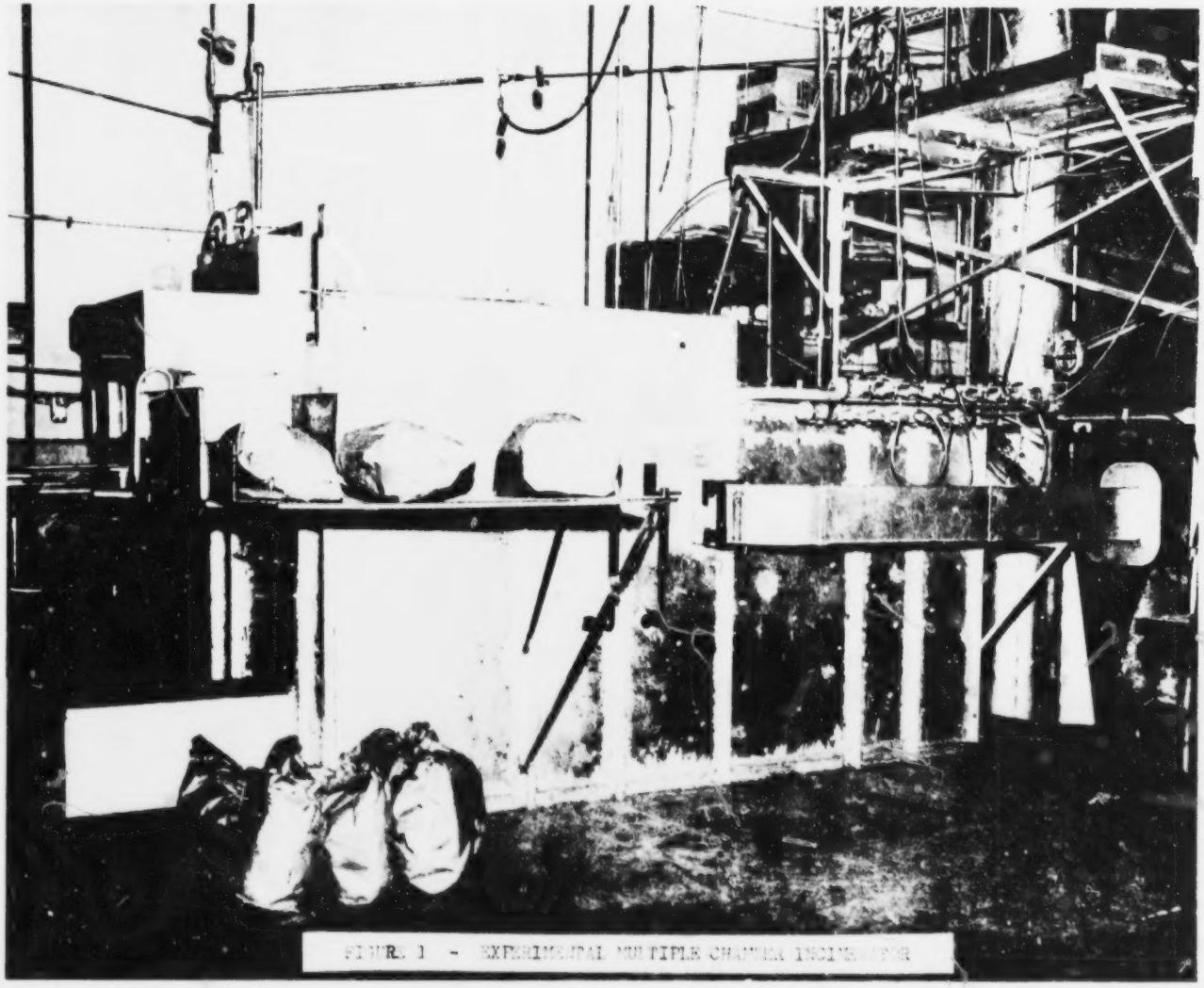
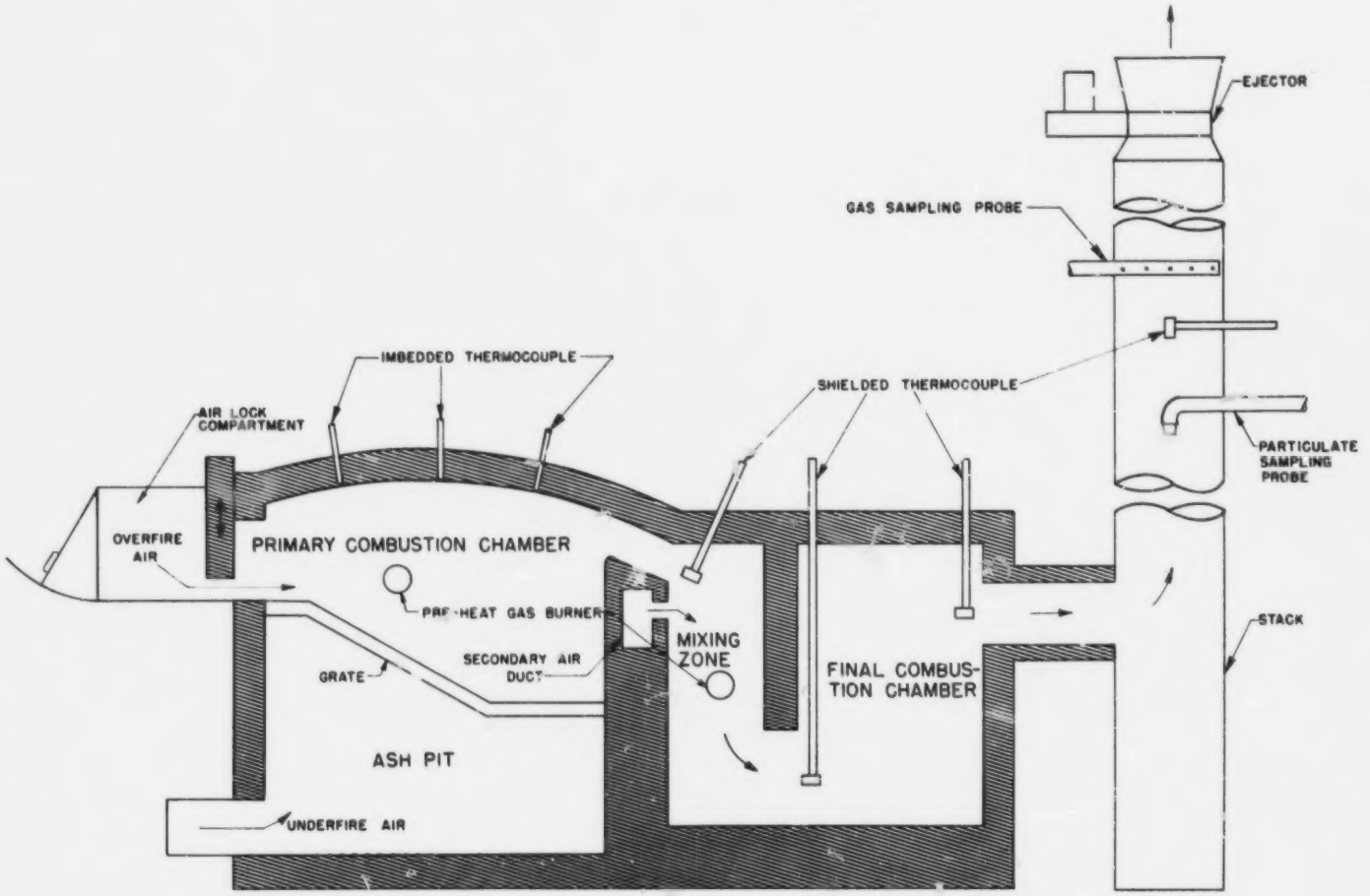
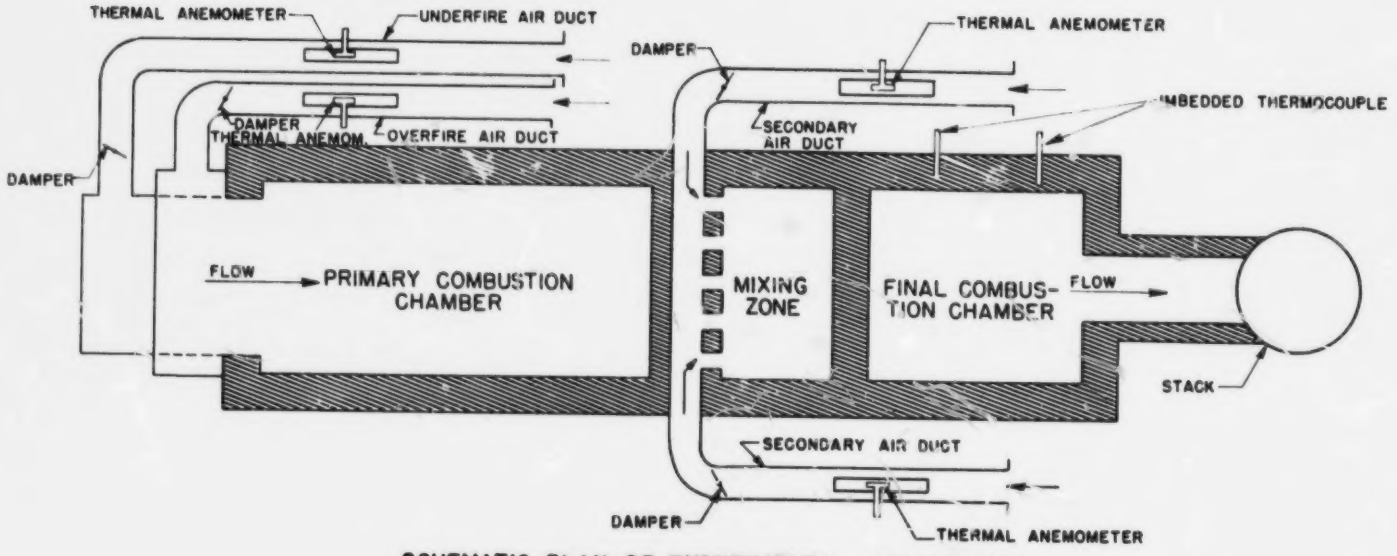


FIGURE 1 - EXPERIMENTAL MULTIPLE CHAMBER INCINERATOR

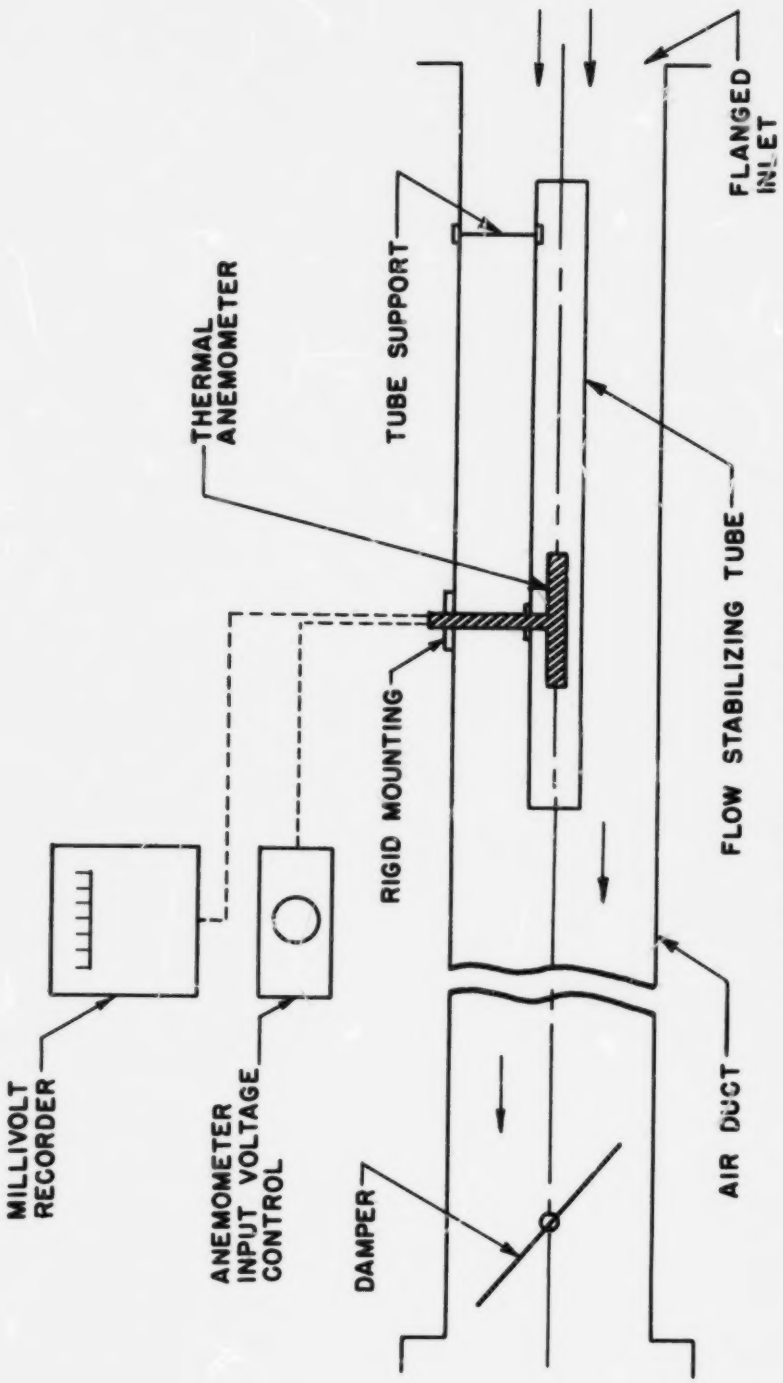


SCHEMATIC ELEVATION OF EXPERIMENTAL MULTIPLE CHAMBER INCINERATOR
FIGURE 2



SCHEMATIC PLAN OF EXPERIMENTAL INCINERATOR
SHOWING AIR—METERING DUCTS

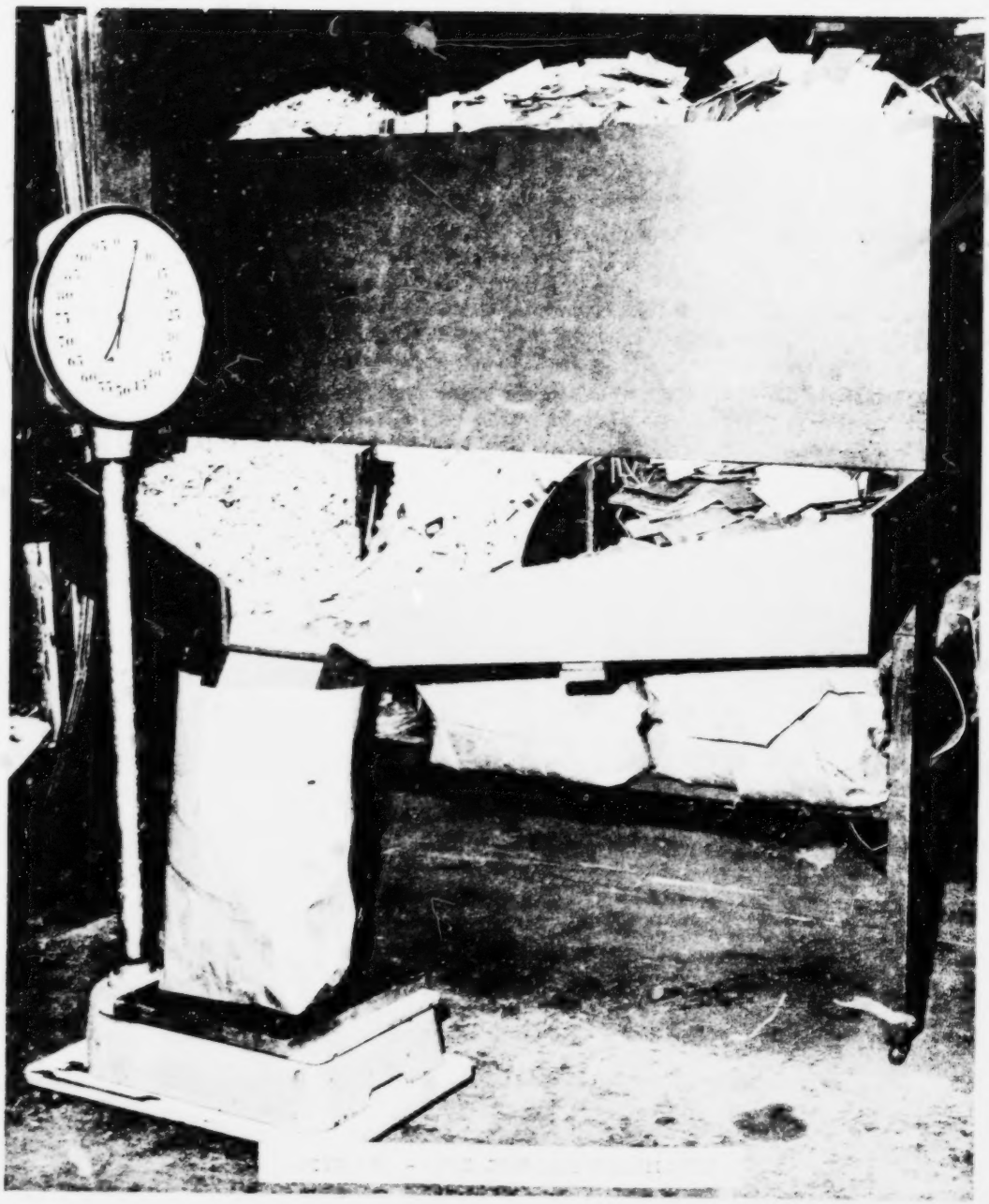
FIGURE 3



ARRANGEMENT FOR MOUNTING OF THERMAL ANEMOMETER IN AIR SUPPLY DUCT

FIGURE 4

FIGURE 5 - FUEL COMPONENTS



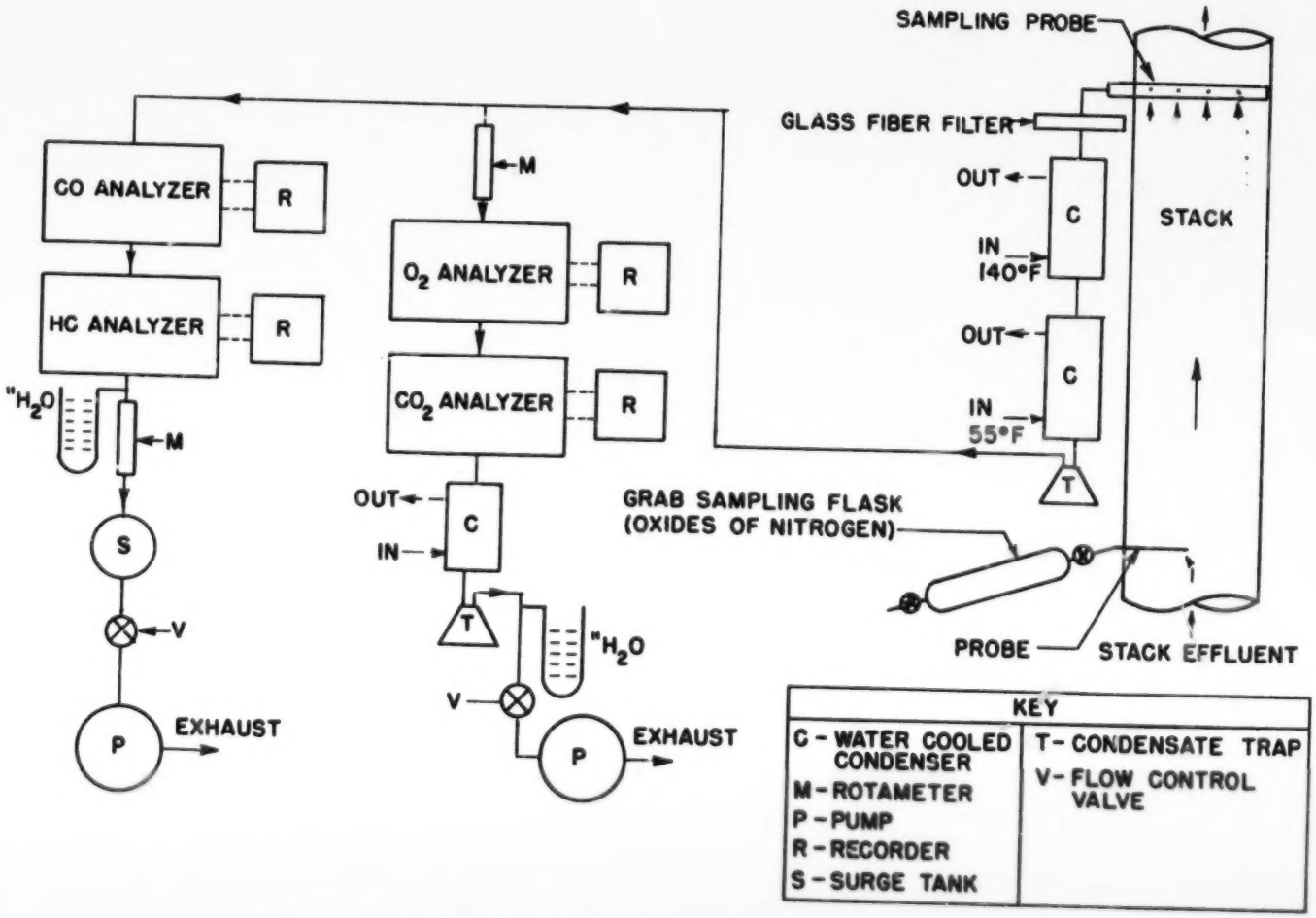


DIAGRAM OF STACK GAS SAMPLING SYSTEM
FIGURE 8

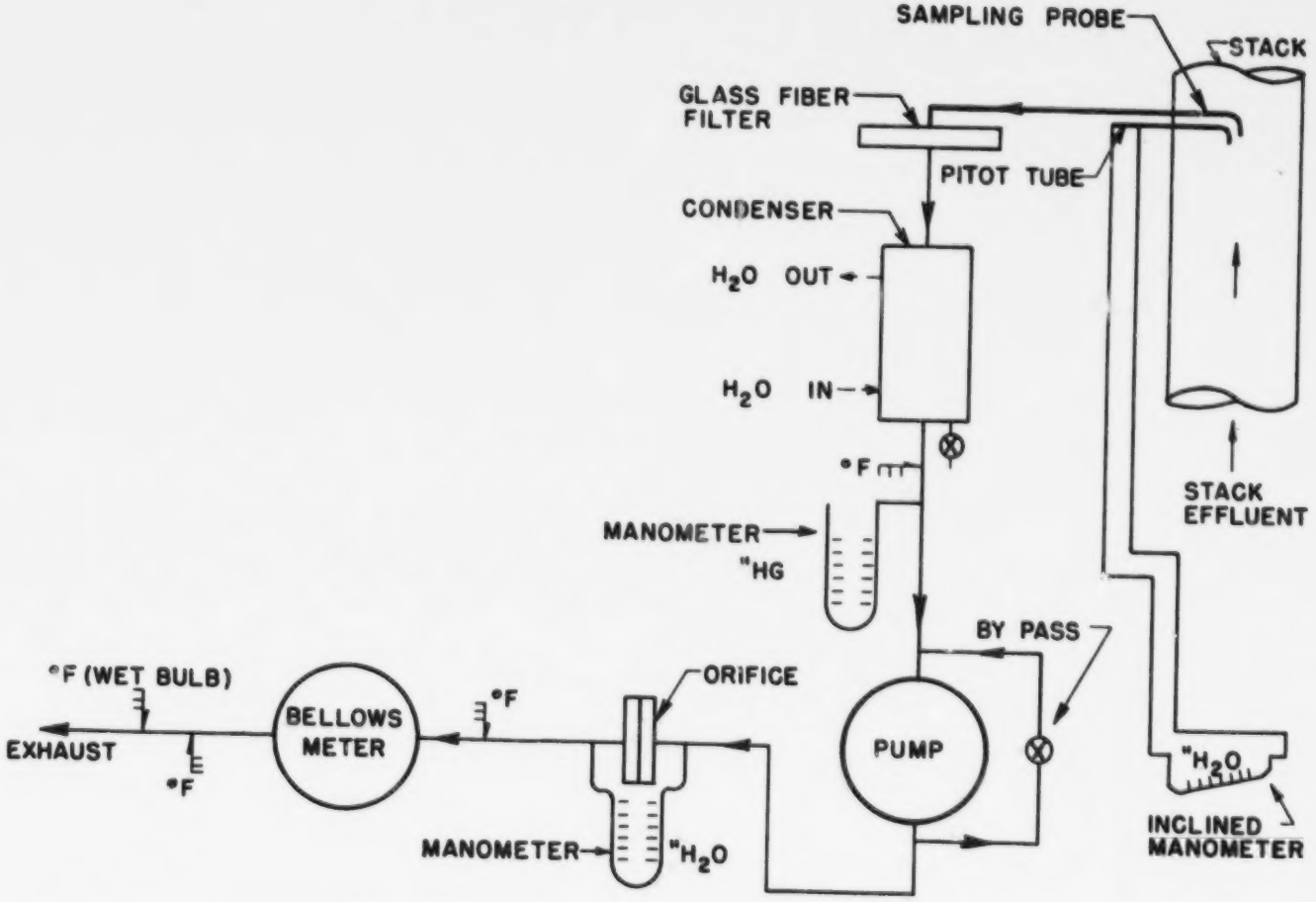
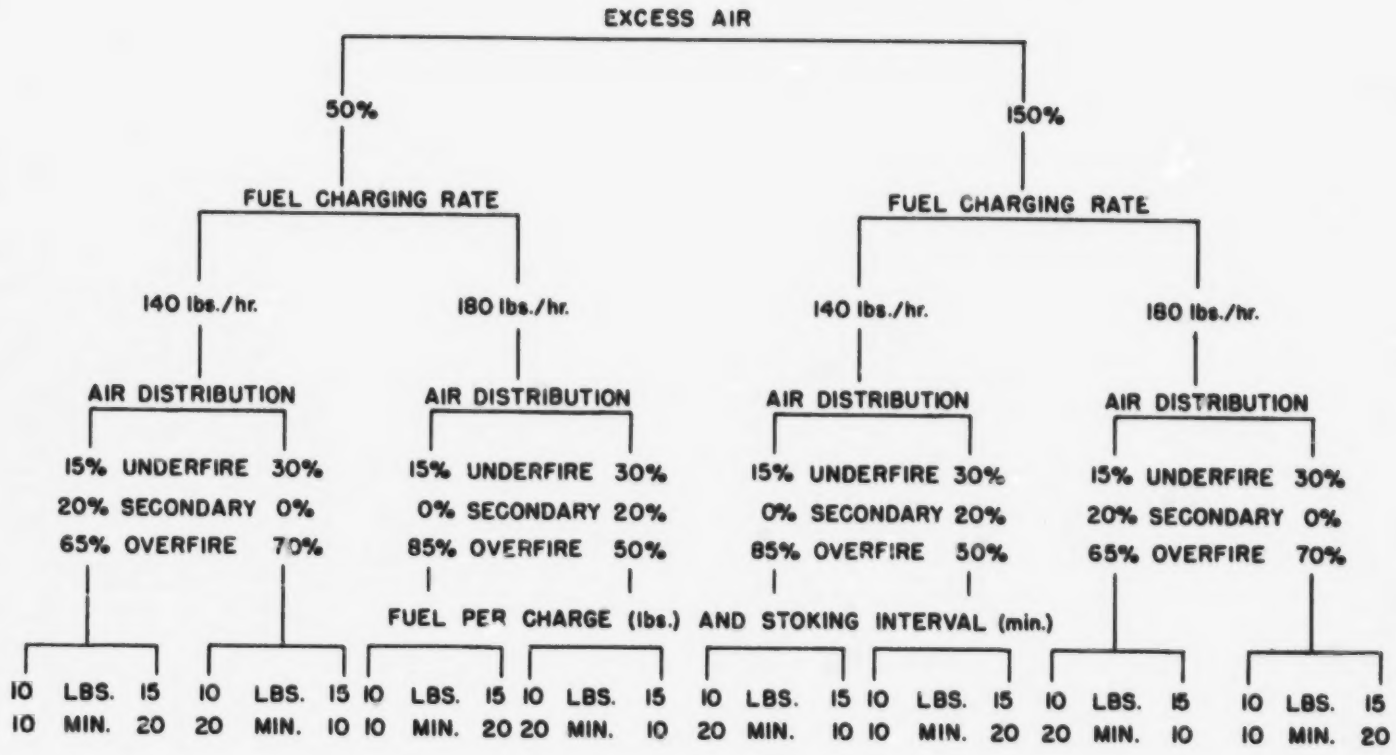


DIAGRAM OF PARTICULATE SAMPLING SYSTEM

FIGURE 9



EXPERIMENT DESIGN

FIGURE 10

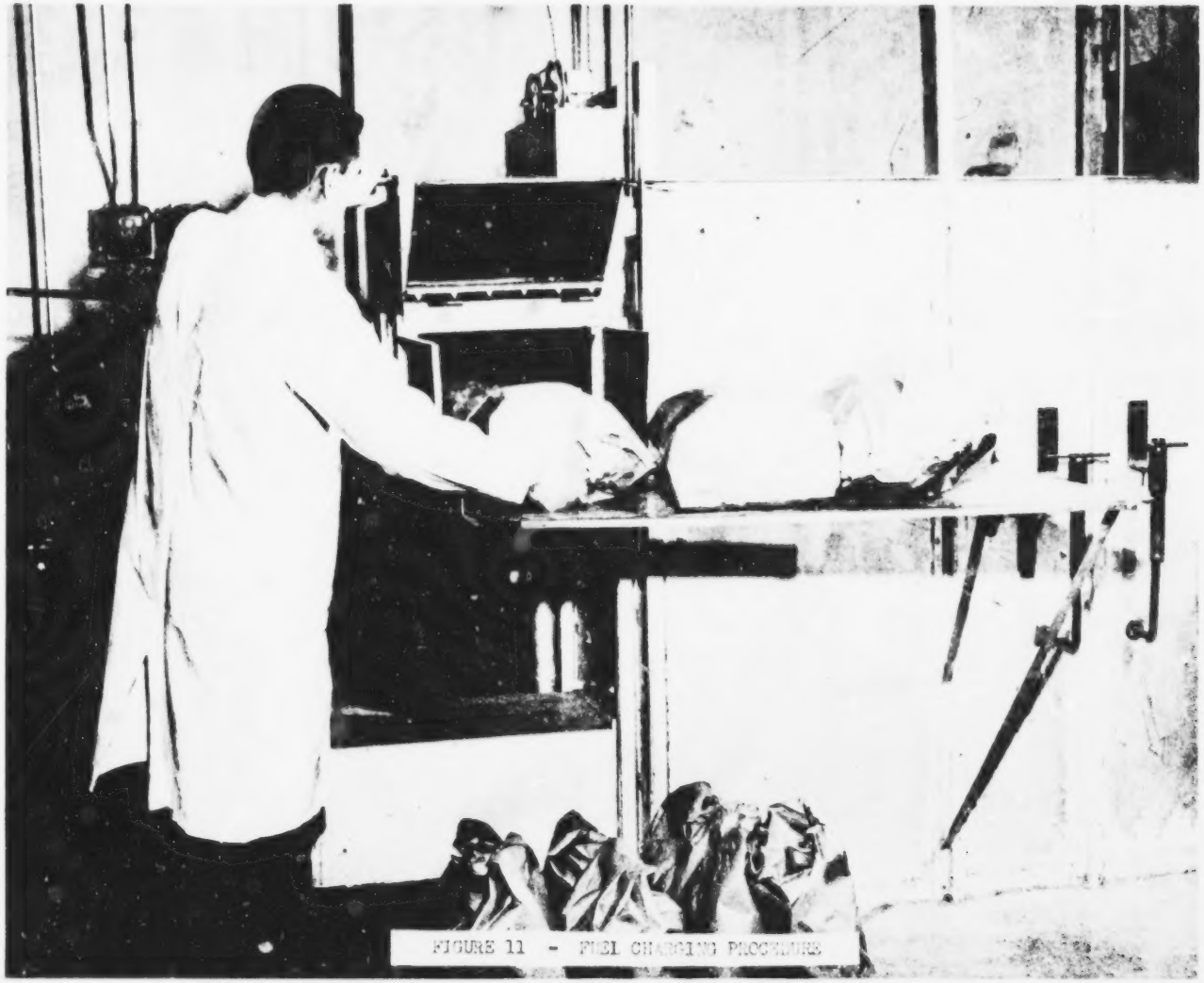
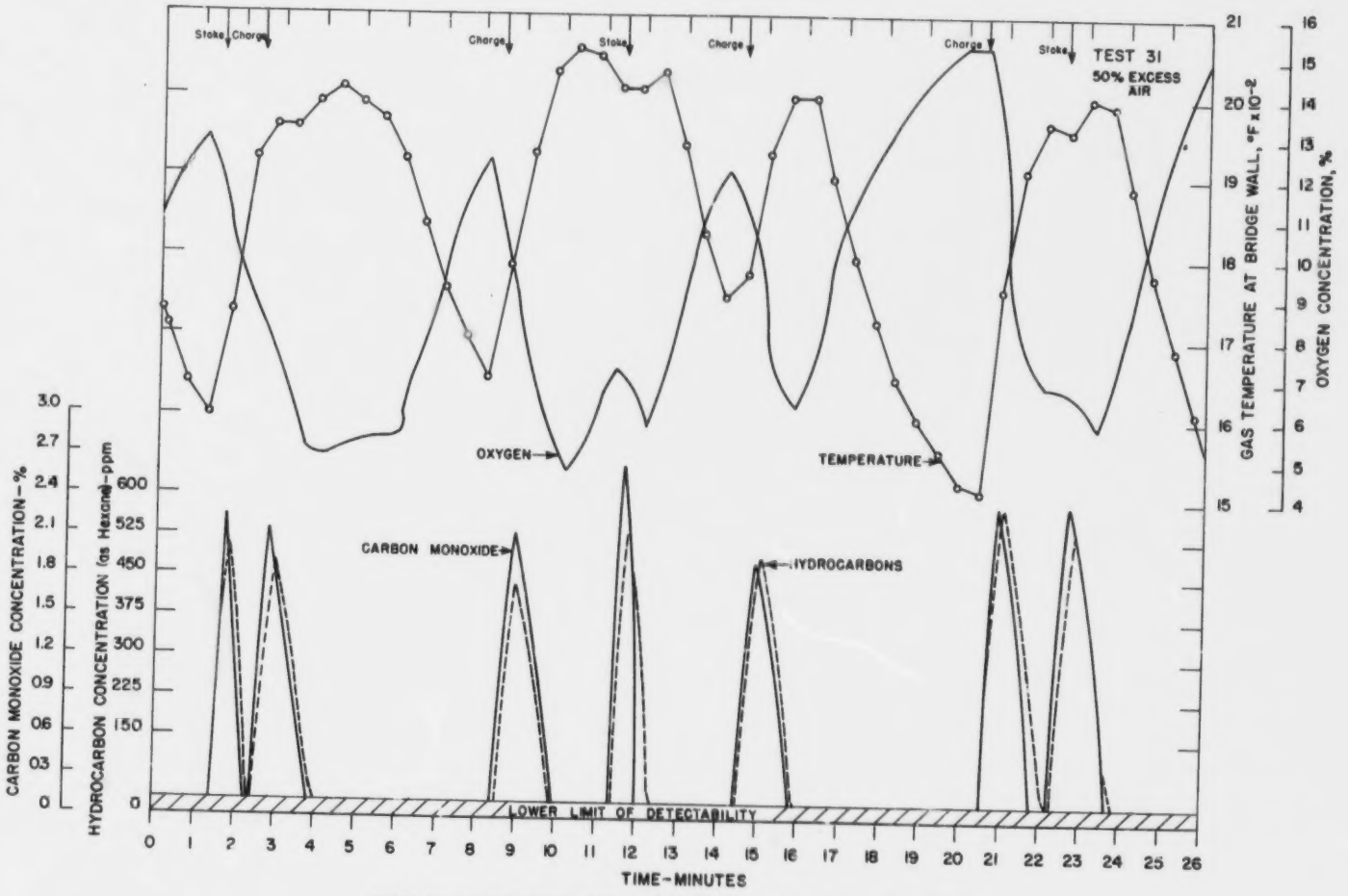
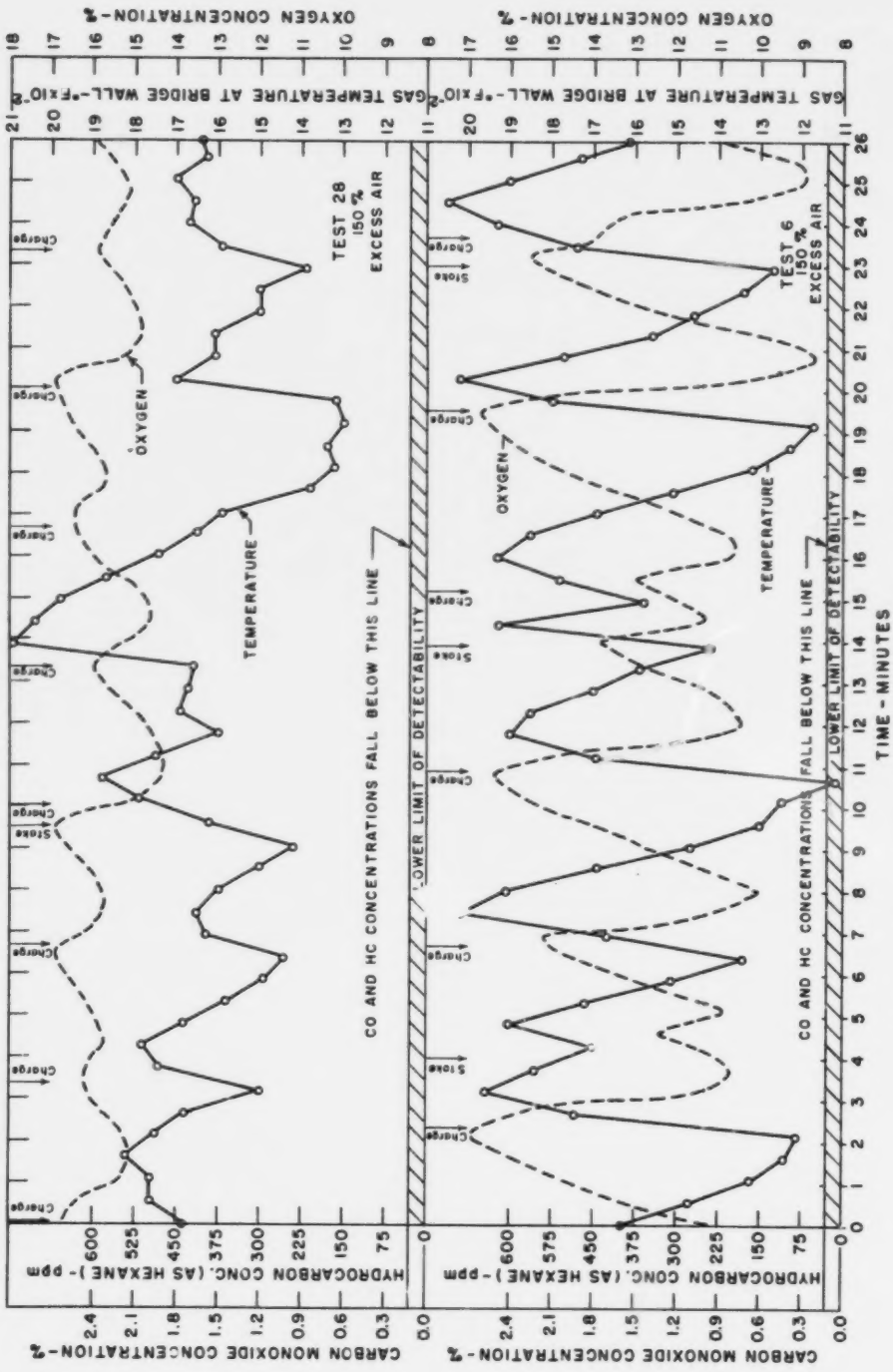


FIGURE 11 - FUEL CHARGING PROCEDURE



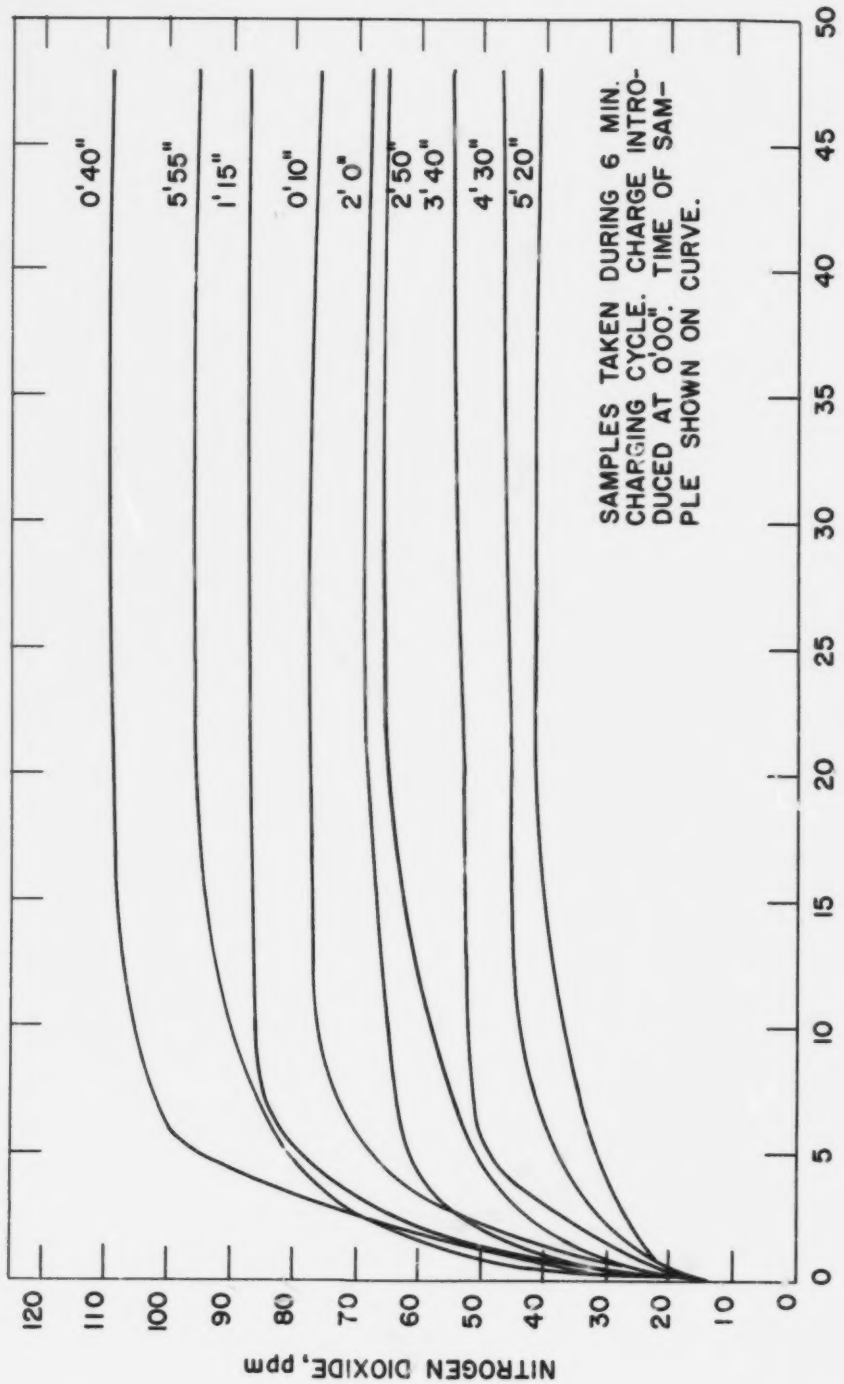
EFFECT OF STOKING AND CHARGING ON CARBON MONOXIDE AND HYDROCARBON PRODUCTION—AT 50% EXCESS AIR

FIGURE 12



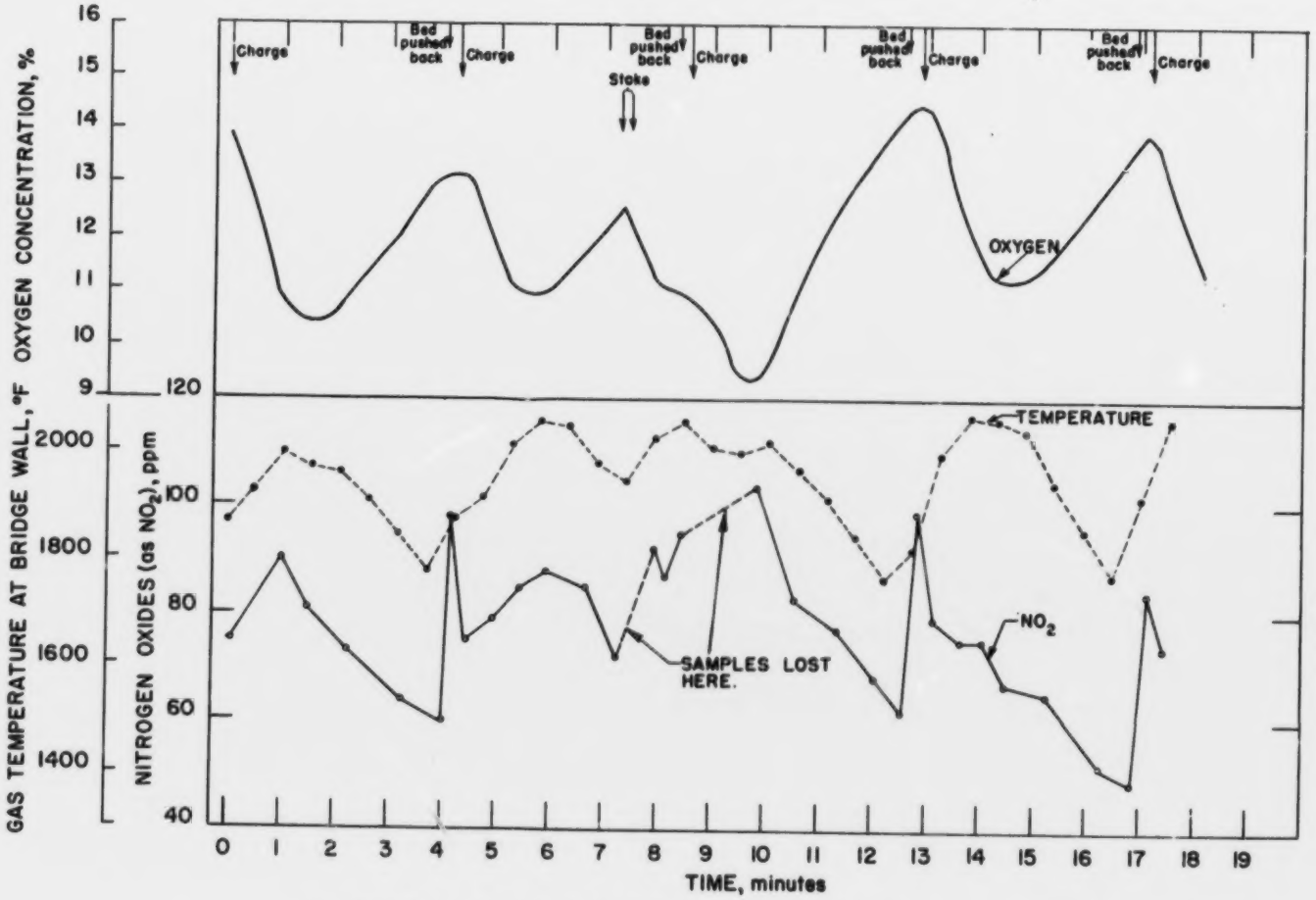
EFFECT OF STOKING AND CHARGING ON CARBON MONOXIDE AND HYDROCARBON PRODUCTION — AT 150 % EXCESS AIR

FIGURE 13



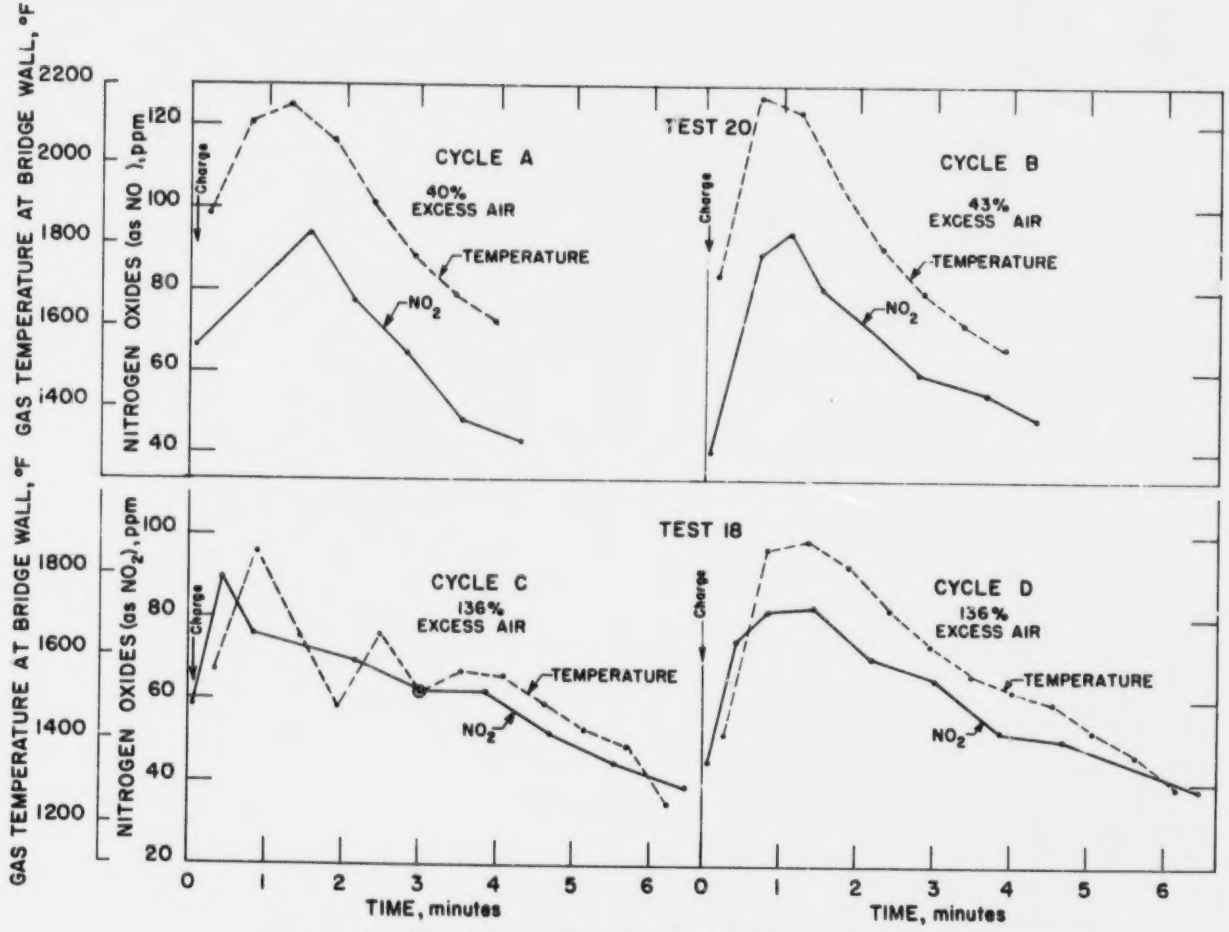
NITROGEN DIOXIDE IN STACK EFFLUENT GRAB SAMPLES
based on analysis with Saltzman Reagent

FIGURE 14



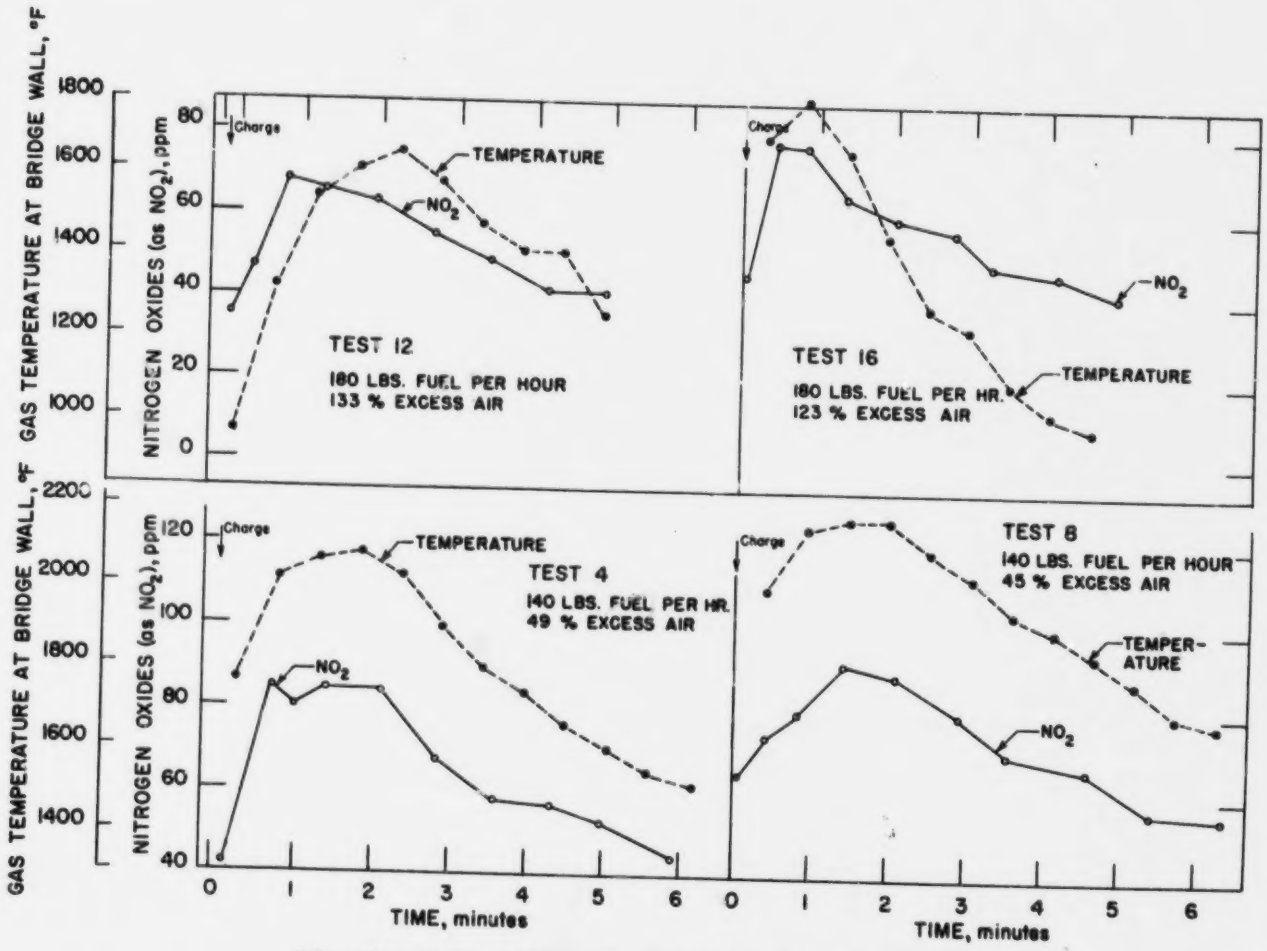
CYCLIC VARIATION OF OXIDES OF NITROGEN AND TEMPERATURE
showing effect of stoking and charging

FIGURE 15

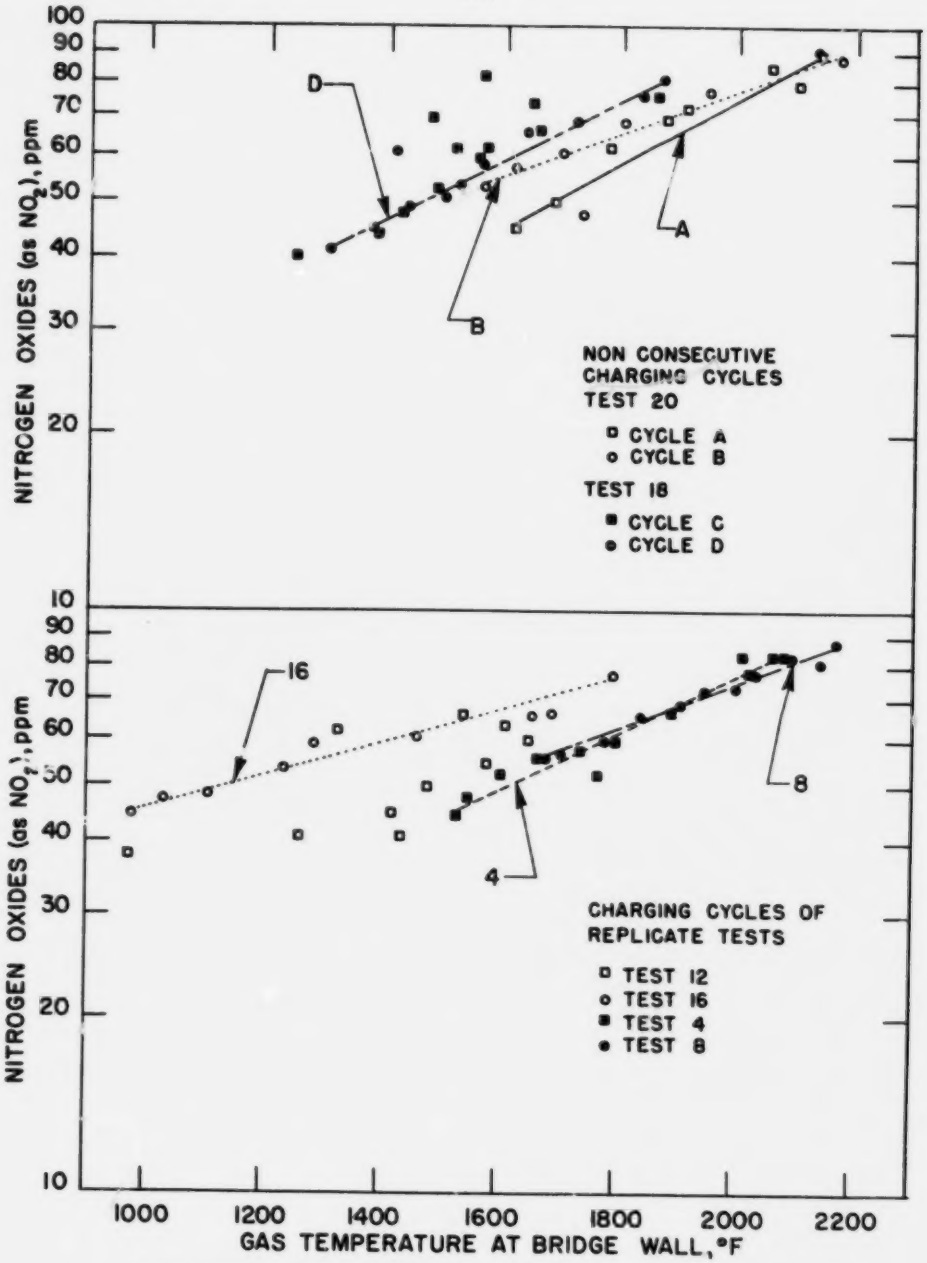


RELATIONSHIP BETWEEN NITROGEN OXIDES AND TEMPERATURE
for two non-consecutive charging cycles

FIGURE 16

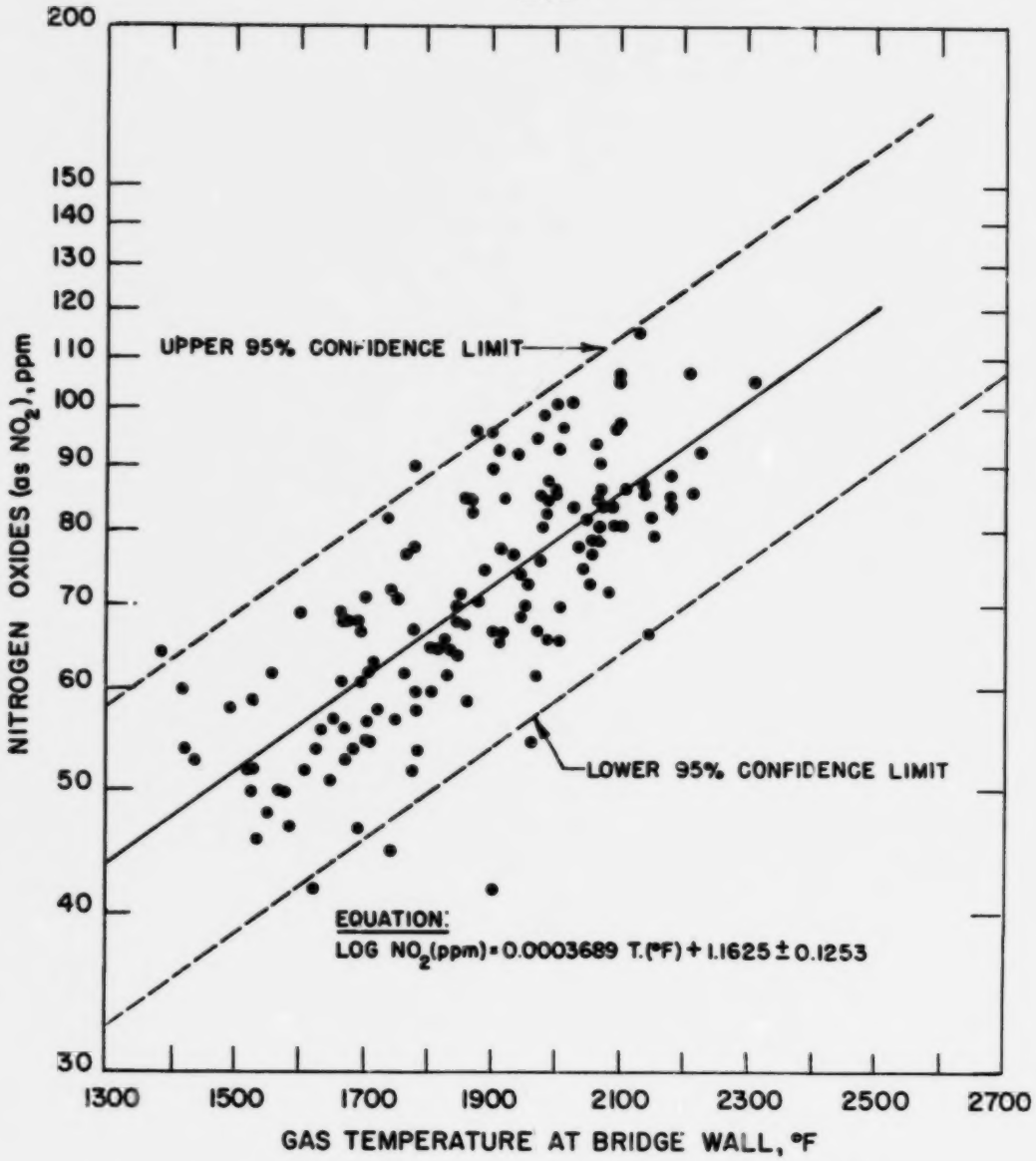


RELATIONSHIP BETWEEN NITROGEN OXIDES AND TEMPERATURE
for charging cycles of replicate tests
FIGURE 17



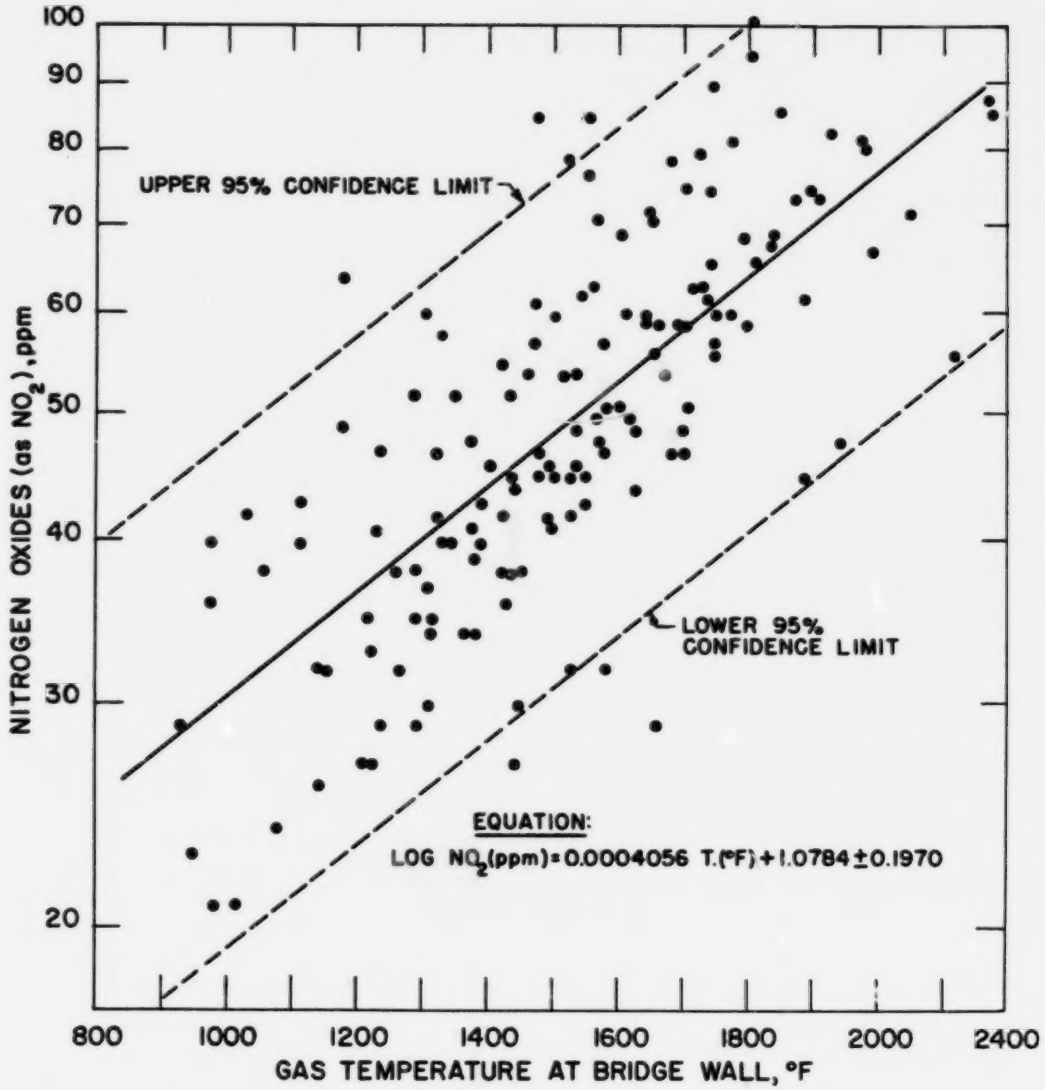
VARIATION OF NITROGEN OXIDES—TEMPERATURE RELATIONSHIP BETWEEN TEST CYCLES

FIGURE 18



RELATIONSHIP OF NITROGEN OXIDES TO TEMPERATURE AT 50% EXCESS COMBUSTION AIR LEVEL (ALL SAMPLES)

FIGURE 19



RELATIONSHIP OF NITROGEN OXIDES TO TEMPERATURE AT 150% EXCESS COMBUSTION AIR LEVEL (ALL SAMPLES)

FIGURE 20

TABLE 1 - RANGE OF COMBUSTION AIR DISTRIBUTION

		Nominal Percentage	Range of Actual Percentages
EXCESS COMBUSTION AIR		50	42 - 49
		150	132 - 148
PERCENT OF TOTAL AIR	UNDER FIRE	15	14 - 16
		30	27 - 30
	SECONDARY	0	0
		20	19 - 22
	OVER FIRE	50	49 - 53
		65	63 - 66
		70	70 - 73
		85	84 - 86

TABLE 2A - SUMMARY OF RESULTS
Operation at 50% Excess Air Level

TEST CONDITIONS			TEST NO.	STACK DISCHARGE (scfm)	PARTICULATES		NITROGEN OXIDES		CARBON MONOXIDE	HYDRO-CARBONS
Fuel Burned	Air Distribution	Fuel per Charge / Stoking Interval			gr/scf	lbs/ton burned	ppm	lbs/ton burned	lbs/ton burned	lbs/ton burned
140 lbs/hr	15% Underfire and 20% Secondary	10 lbs / 10 min	11	250	0.11	1.6	80	2.1	12.	0.72
			15	240	0.044	1.3	83	2.0	0.00	0.00
		15 lbs / 20 min	4	230	0.034	0.96	66	1.6	-	-
			8	230	0.068	1.9	74	1.7	9.8	0.78
	30% Underfire and 0% Secondary	10 lbs / 20 min	20	220	0.22	5.9	69	1.6	28.	2.1
			24	270	0.13	4.1	65	1.8	18.	0.82
		15 lbs / 10 min	27	270	0.17	5.7	74	2.1	-	-
			31	250	0.21	6.4	65	1.6	26.	2.5
180 lbs/hr	15% Underfire and 0% Secondary	10 lbs / 10 min	10	330	0.049	1.6	62	1.6	4.8	0.50
			14	320	0.10	3.2	79	2.0	6.1	0.47
		15 lbs / 20 min	1	320	0.068	2.1	78	2.0	-	-
			5	300	0.057	1.6	85	2.0	4.3	0.00
	30% Underfire and 20% Secondary	10 lbs / 20 min	17	300	0.27	8.6	79	2.1	24	1.4
			21	310	0.086	2.5	95	2.3	7.7	0.37
		15 lbs / 10 min	26	320	0.15	4.4	91	2.3	-	-
			30	330	0.072	2.3	75	2.0	8.0	0.64

TABLE 2B - SUMMARY OF RESULTS
Operation at 150% Excess Air Level

TEST CONDITIONS			TEST NO.	STACK DISCHARGE (scfm)	PARTICULATES		NITROGEN OXIDES		CARBON MONOXIDE	HYDRO-CARBONS
Fuel Burned	Air Distribution	Fuel per Charge / Stoking Interval			gr/scf	lbs/ton burned	ppm	lbs/ton burned	lbs/ton burned	lbs/ton burned
140 lbs/hr	15% Underfire and 0% Secondary	10 lbs / 20 min	25	400	0.047	2.3	51	2.1	-	-
			29	390	0.042	2.0	53	2.1	0.0C	0.00
		15 lbs / 10 min	18	380	0.037	1.7	63	2.4	0.00	0.00
			22	440	0.037	2.0	64	2.9	0.00	0.00
	30% Underfire and 20% Secondary	10 lbs / 10 min	2	400	0.040	2.0	48	1.9	-	-
			6	370	0.036	1.6	54	2.0	0.00	0.00
		15 lbs / 20 min	9	350	0.038	1.6	63	2.2	4.3	0.00
			13	370	0.024	1.1	52	2.0	0.00	0.00
180 lbs/hr	15% Underfire and 20% Secondary	10 lbs / 20 min	28	490	0.036	1.7	75	2.9	0.00	0.00
			32	480	0.035	1.6	60	2.2	0.00	0.00
		15 lbs / 10 min	19	510	0.029	1.4	47	1.9	0.00	0.00
			23	490	0.034	1.6	66	2.6	0.00	0.00
	30% Underfire and 0% Secondary	10 lbs / 10 min	3	500	0.058	2.8	60	2.4	-	-
			7	530	0.042	2.1	55	2.3	0.00	0.00
		15 lbs / 20 min	12	490	0.035	1.6	54	2.1	0.00	0.00
			16	450	0.036	1.6	58	2.1	0.00	0.00

TABLE 3 - GEOMETRIC MEAN PARTICULATE DISCHARGE

(Means of Eight Tests)

	Lbs. particulate/hour		Lbs. particulate/lb. fuel burned	
	50% Excess Air	150% Excess Air	50% Excess Air	150% Excess Air
15% Underfire Air	1.18×10^{-1}	1.32×10^{-1}	7.39×10^{-4}	8.32×10^{-4}
30% Underfire Air	3.64×10^{-1}	1.39×10^{-1}	22.91×10^{-4}	8.75×10^{-4}

TABLE 4 - GEOMETRIC MEAN OF NITROGEN OXIDES DISCHARGE

(Means of Eight Tests)

	Lbs. NO_2/hour			Lbs. NO_2/lb. fuel burned		
	50% Excess Air	150% Excess Air	Average	50% Excess Air	150% Excess Air	Average
140 lbs. fuel/hr.	1.26×10^{-1}	1.49×10^{-1}	1.37×10^{-1}	9.02×10^{-4}	10.65×10^{-4}	9.80×10^{-4}
180 lbs. fuel/hr.	1.93×10^{-1}	2.03×10^{-1}	1.98×10^{-1}	10.70×10^{-4}	11.28×10^{-4}	10.98×10^{-4}
Average	1.56×10^{-1}	1.74×10^{-1}		9.82×10^{-4}	10.96×10^{-4}	

TABLE 5 - INCINERATOR DIMENSIONS AND GAS VELOCITY RANGES

ZONE	DIMENSIONS		AREA OF CROSS SECTION	GAS VELOCITY RANGE*	
	ft. (Unless otherwise shown)		ft^2	ft/sec	
				50% Excess Air	150% Excess Air
Primary Combustion Chamber	Length Width Maximum Arch Height Above Grate	4.1 2.1 2.7	-	-	-
Flame Port	Width Height	2.08 0.46	0.96	14 to 24	19 to 34
Mixing Chamber	Length Width	1.2 2.1	2.5	6 to 10	9 to 13
Curtain Wall Port	Width Height	1.9 1.1	2.1	5 to 8	7 to 11
Secondary Combustion Chamber	Length Width Height	2.3 2.1 3.4	4.8 (LxW)	3 to 5	4 to 6
Grates	Pipe O.D. (inches) Separation (inches)	1.3 0.4	1.9	0.3 to 0.8	0.5 to 1.3

*Based on Average Cycle Temperature